Two-Phase Cooling of Power Electronics

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National Renewable Energy Laboratory

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Project ID: APE037

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Overview

Timeline

- **Project Start Date:** FY11
- **Project End Date:** FY14
- **Percent Complete:** 90%

Barriers

- **Barriers addressed:**
  - weight
  - cost
  - efficiency

Budget

- **Total Project Funding: $1,960K**
  - DOE Share: **$1,960K**
- **Funding Received in FY13: $400K**
- **Funding for FY14: $460K**

Partners

- **Delphi**
- **3M**
- **DuPont**
- **University of Colorado-Boulder**
- **Iowa State University**
- **University of Illinois-Chicago**
- **Project lead: National Renewable Energy Laboratory**

Relevance

Objective

- Significantly improve thermal management of automotive power electronics by utilizing the high heat transfer rates of two-phase cooling.
    - Design and build a passive two-phase cooling system for automotive power modules (cool six Delphi discrete power switches). Demonstrate that the system dissipates automotive heat loads and provides superior thermal performance.
    - Quantify key system metrics (thermal resistance, coefficient of performance, volume, weight) and compare with conventional cooling systems.

Motivation

- Accelerate the adoption of electric-drive vehicles through improved thermal management.
    - Reduce power electronics **cost** and increase **power density, specific power**, and **efficiency**.

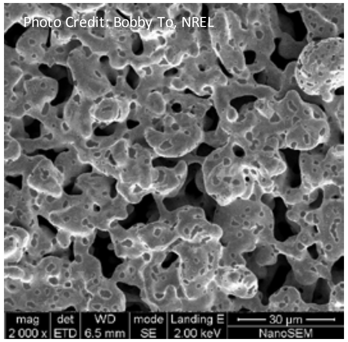
Milestones

Month / Year	Milestone or Go/No-Go Decision
September 2013	**Go/No-Go Decision:** Demonstrated that the passive two-phase cooling system can dissipate at least 3.5 kW of heat with only 250 mL of refrigerant. • 3.5 kW of heat is an estimate of the maximum power electronics heat output for a 55 kW inverter.
November 2013	**Milestone:** Experimentally measured the condenser thermal resistance and evaluated methods to enhance condensation heat transfer. • Conducted analysis to estimate the required condenser size at various refrigerant temperatures.
January 2014	**Milestone:** Conducted analysis on an advanced evaporator design. Modeling predicted advanced evaporator can reduce thermal resistance by 58% to 65% compared with the state-of-the-art automotive cooling systems.
April 2014	**Milestone**: Experimentally characterized the thermal resistance of the advanced evaporator design. • Bonded a Delphi power module to the evaporator using a thermoplastic interface and measured the junction-to-liquid thermal resistance.
June 2014	**Milestone:** Evaluate the effect of inclination/orientation on the two-phase cooling system thermal performance.

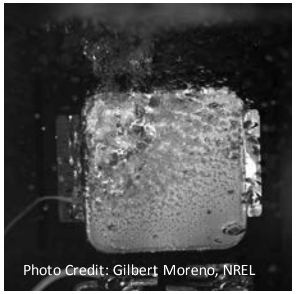
Approach/Strategy

Fundamental Research | **Module-Level Research** | **Inverter-Scale Demonstration**

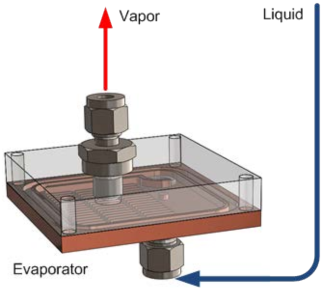
Characterized performance of HFO-1234yf and HFC-245fa.



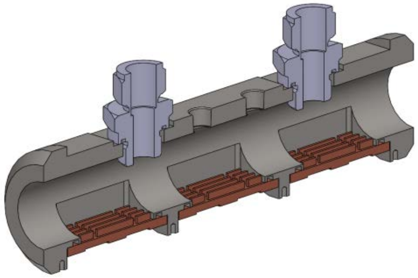
Achieved heat transfer rates of up to ~200,000 W/m^2-K.



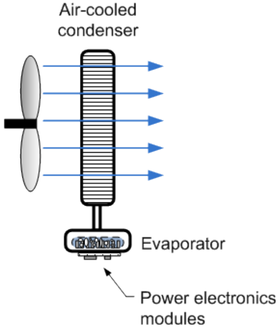
Reduced thermal resistance by over 60% using immersion two-phase cooling of a power module.



Quantified refrigerant volume requirements.



Dissipated 3.5 kW of heat with only 250 mL of refrigerant.



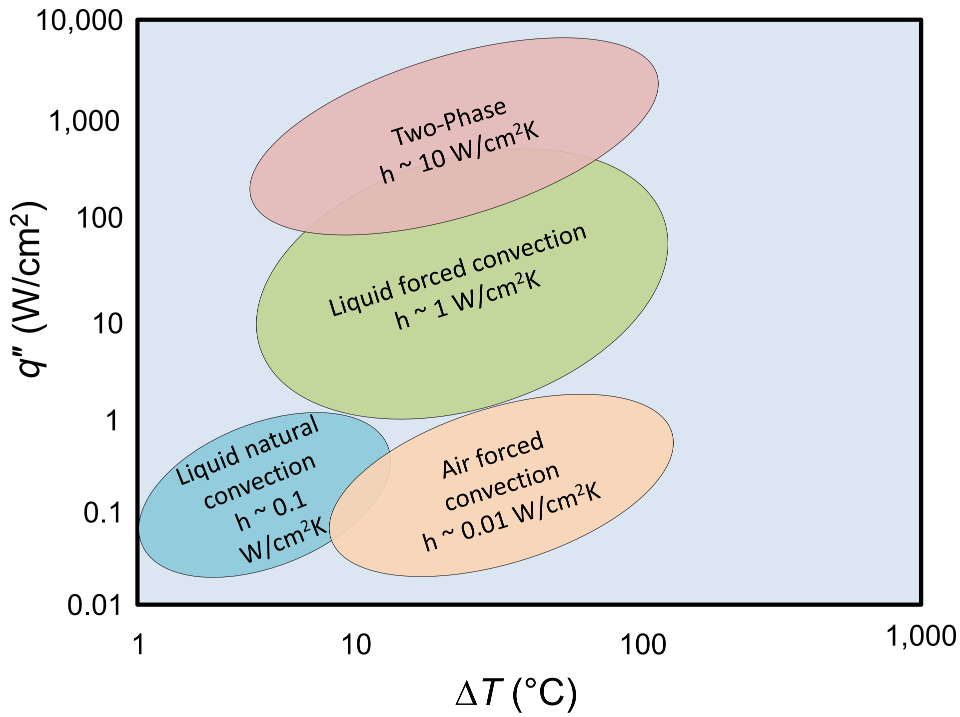
Predicted 58%-65% reduction in thermal resistance via indirect and passive two-phase cooling.

Approach/Strategy

Impacts

The high heat transfer rates and isothermal characteristics of two-phase cooling can:

- Enable cost reductions (decrease semiconductor device size/count) through increased power density.
- Increase efficiency through a passive (no pumping requirement) two-phase cooling approach.



Adapted from: I. Mudawar, et al., 2008, "Two-Phase Spray Cooling of Hybrid Vehicle Electronics,"

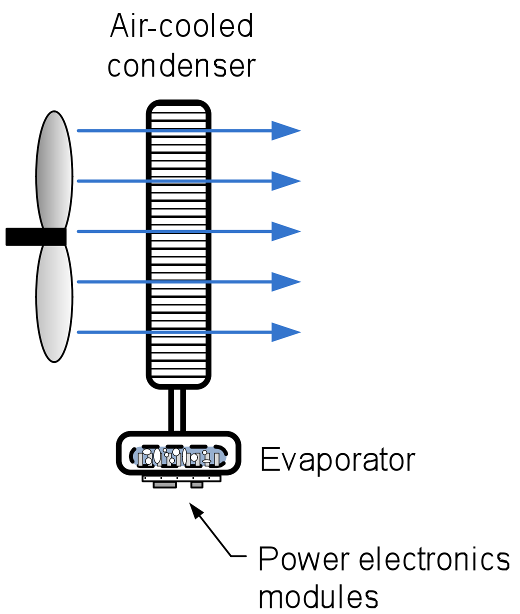
Uniqueness

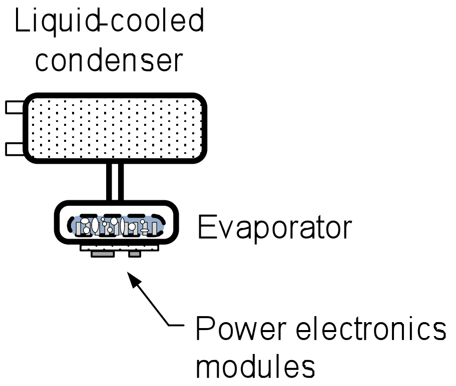
- Two-phase cooling (although used to cool vehicle cabin) is not used to cool power electronics in vehicles.
- Use of HFO-1234yf (new, environmentally friendly refrigerant) to cool electronic devices.

Approach/Strategy

Passive Two-Phase Cooling Concept/Strategy

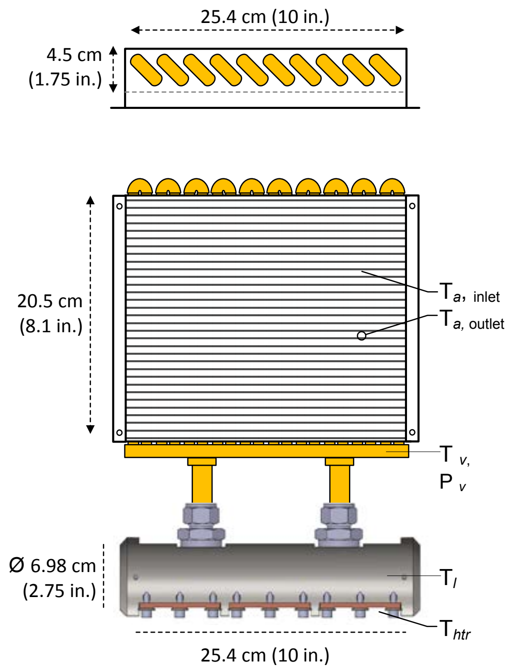
- Ease of implementation via an indirect-cooling approach (devices not in contact with refrigerant).
- Increased efficiency through a passive (no pump or compressor) two-phase cooling approach.
- Use of automotive air-conditioning refrigerant (HFO-1234yf) and a lower pressure alternative (HFC-245fa).
- Evaluate liquid-cooled condenser to decrease condenser size. Liquid-cooled condenser may allow use of waste heat for cabin heating (integrated thermal management).





Technical Accomplishments and Progress

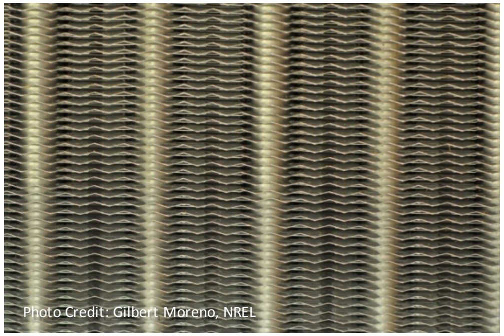
Designed and Fabricated a Proof-of-Concept Two-Phase Cooling System



- Designed to cool three half bridges (inverter-scale). Can accommodate six Delphi power modules.
- Refrigerants: HFO-1234yf and HFC-245fa
- Refrigerant charge: 250 mL
- Maximum operating pressure: 1 MPa (150 psig).

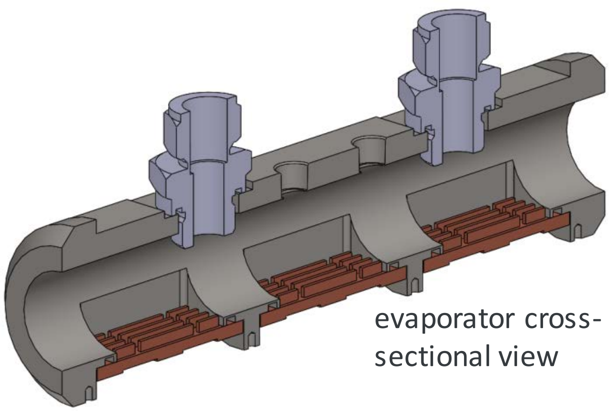
Condenser

- Surface area: air-side: ~2.9 m^2, condensation-side: 0.12 m^2
- 17.8-cm (7-in.) diameter fan: total parasitic power: 38 W, ~250 cfm



finned-tube heat exchanger

Evaporator

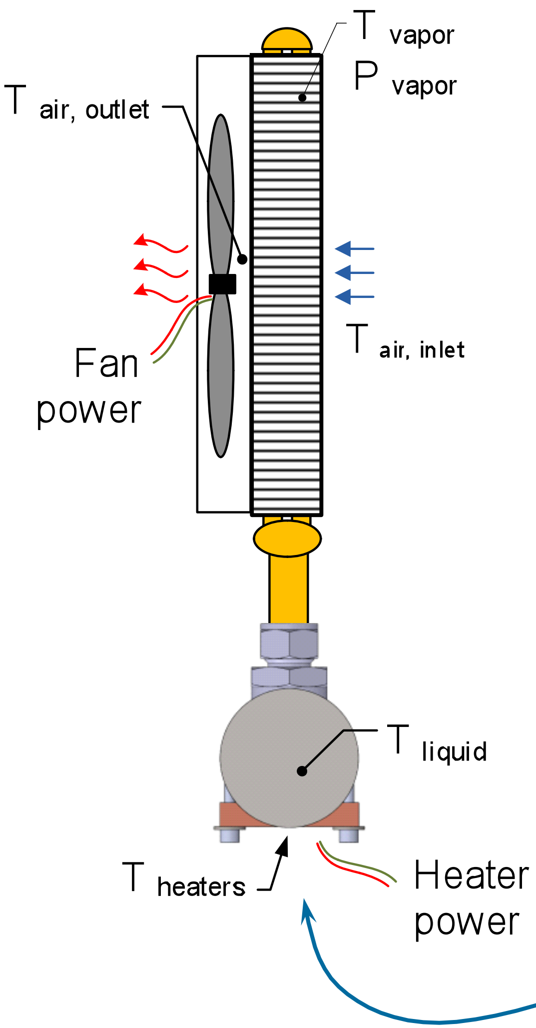


evaporator cross-sectional view

- Interchangeable cold plate design
- Designed to cool one half bridge per cold plate

Technical Accomplishments and Progress

Testing Procedures

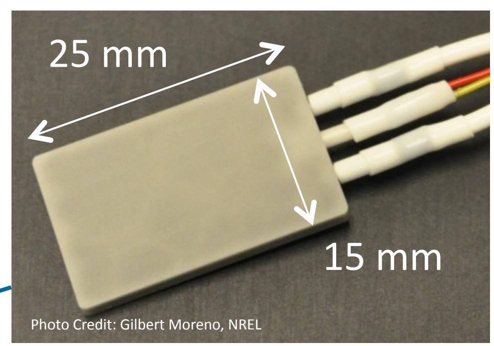


Condenser thermal resistance:

$$R''_{th} = \frac{(T_{vapor} - \bar{T}_{inlet\ air})}{Heat\ dissipated} \times Condenser\ frontal\ area$$

Evaporator thermal resistance:

$$R''_{th} = \frac{(\bar{T}_{heaters} - T_{liquid})}{Heat\ dissipated} \times Total\ heater\ area$$



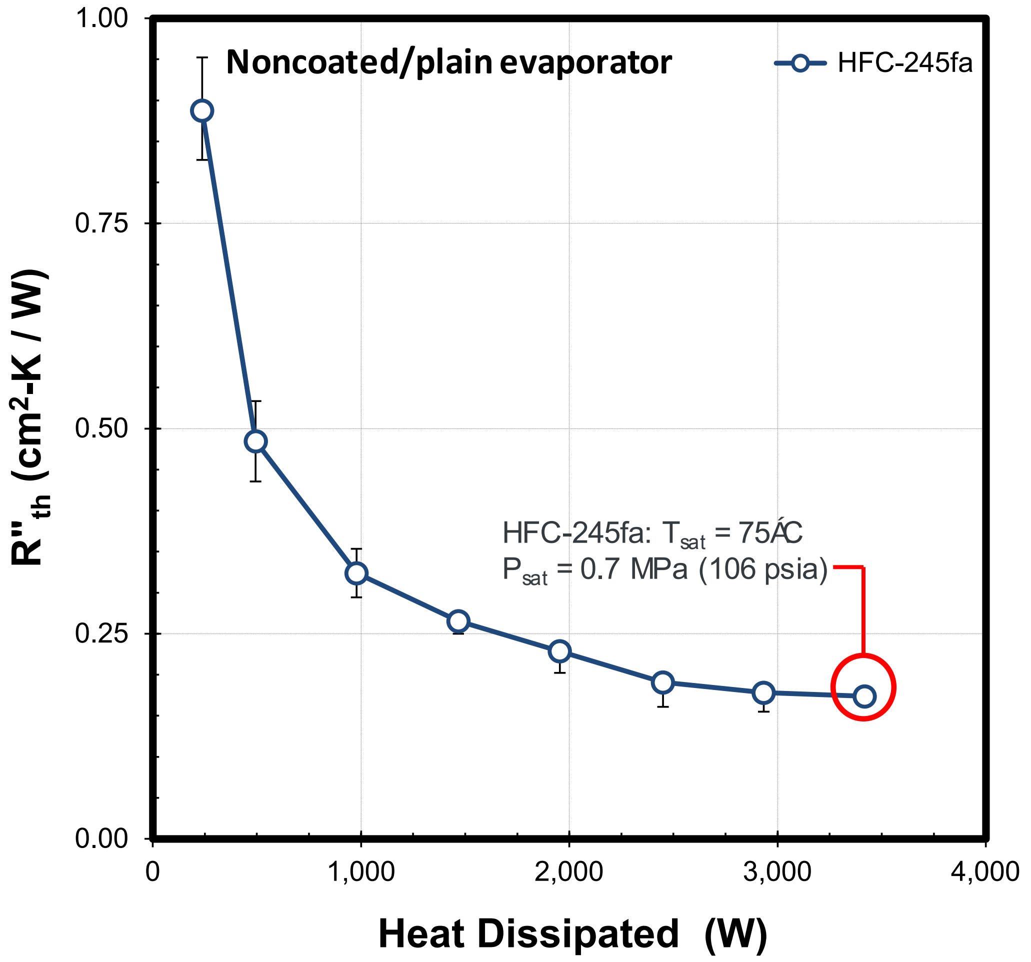
- Initial test conducted using six ceramic heaters that were attached to evaporator using thermal grease.
- Six heaters represent six power switches (inverter-scale).
- Maximum power output from the six heaters is 3.5 kW.

Technical Accomplishments and Progress

Evaporator Thermal Resistance

HFC-245fa (250 mL, 330 grams)

- Demonstrated that the passive two-phase cooling system can dissipate at least 3.5 kW of heat (steady-state) with only 250 mL HFC-245fa.
  - **Significance:** 3.5-kW estimate of the maximum heat dissipated by a 55-kW inverter.
- Heat dissipation can be increased beyond 3.5 kW using microporous (boiling enhancement) coatings. Previous fundamental research demonstrated that 3M microporous coating can increase critical heat flux by 50%.

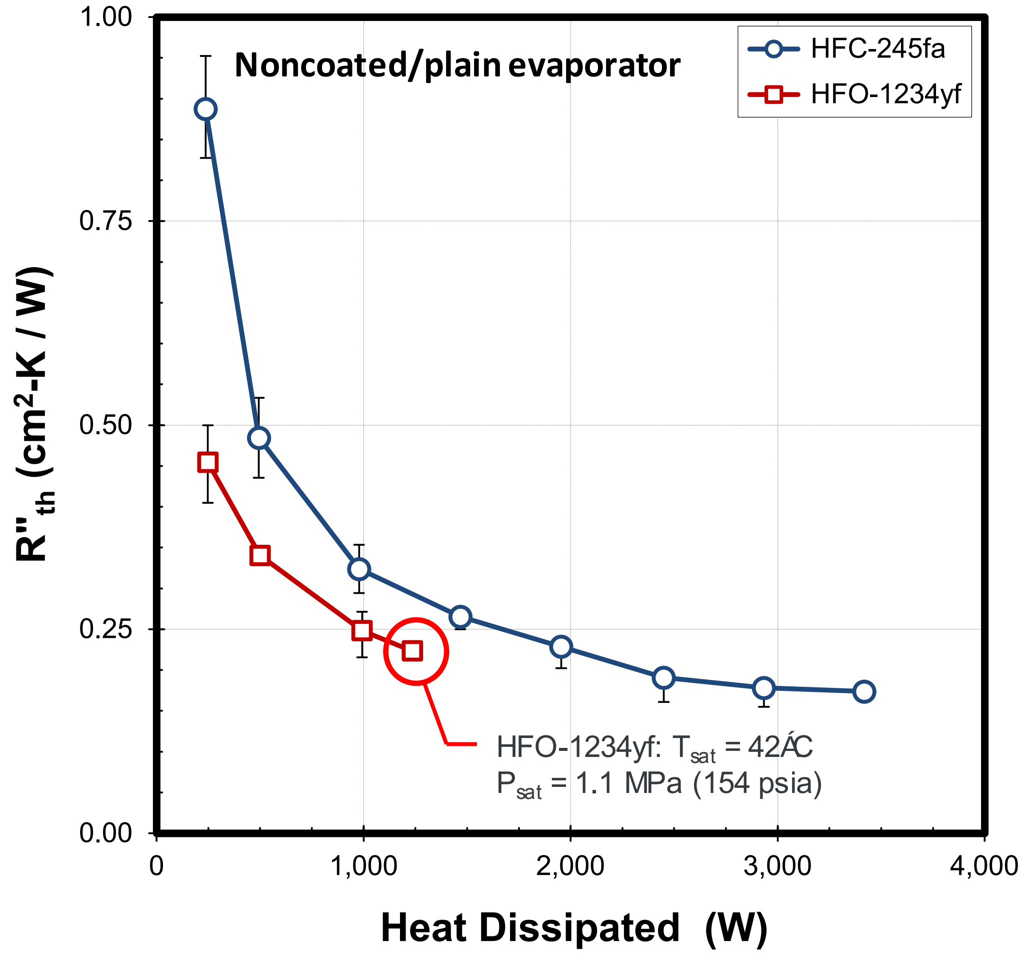


Technical Accomplishments and Progress

Evaporator Thermal Resistance

HFO-1234yf (250 mL, 280 grams)

- Prototype limited heat dissipation to 1.3 kW with HFO-1234yf because of higher pressures. Expect we could dissipate more heat by increasing system pressure capacity.
- HFO-1234yf's higher heat transfer coefficients resulted in lower evaporator thermal resistance.

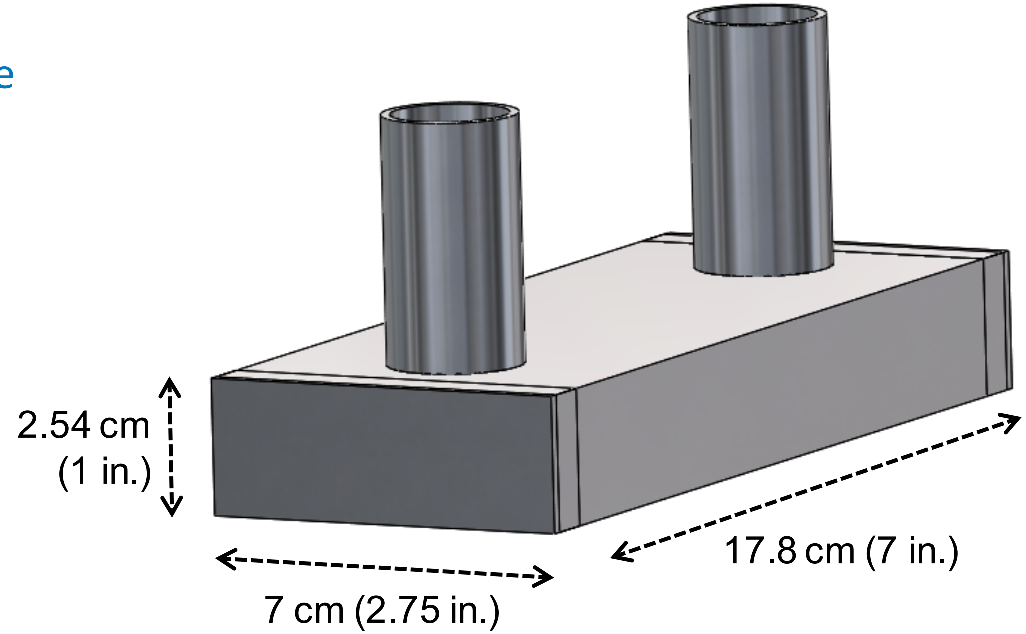


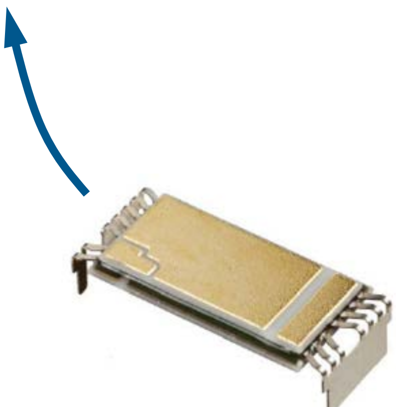
Technical Accomplishments and Progress

Advanced Evaporator Design

Identified techniques to increase performance and reduce the size of the evaporator (record of invention submitted):

- Designed to cool six Delphi power modules.
- Increased evaporation surface area to improve thermal performance.
- Fabricated from low-cost materials (aluminum) and low-cost manufacturing techniques.
- Reduced refrigerant requirements to 180 mL, (HFO-1234yf = 200 g, HFC-245fa = 240 g).
    - **Comparison**: 2010 Toyota Camry air conditioning system uses 510 grams of R-134a (source: autozone.com).

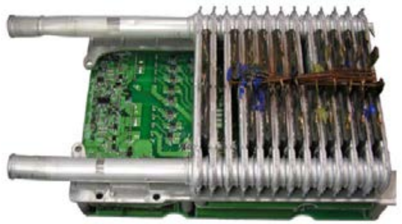




Delphi power module:
Image courtesy of Delphi

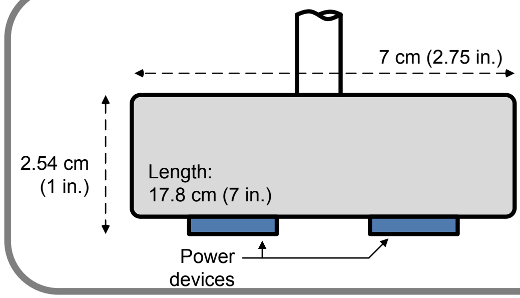
Technical Accomplishments and Progress

Conducted Finite Element Analysis to Estimate Performance of Advanced Evaporator Design

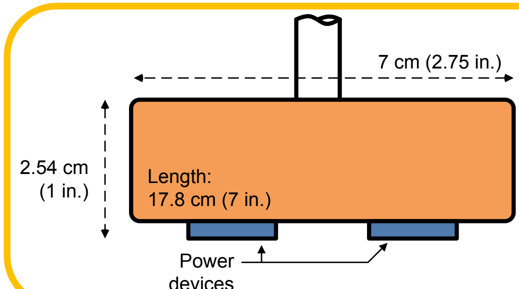


Double-side cooled inverter

Image courtesy of Oak Ridge National Lab



Indirect two-phase cooling (aluminum evaporator)



Indirect two-phase cooling (copper evaporator)

	R''_{th} (mm^2- K/W)	% R''_{th} Reduction
Lexus Hybrid (2008) double-side cooled modules	33.2*	-
Two-phase: aluminum evaporator (***finite element analysis results***)	**13.9**	**58%**
Two-phase: copper evaporator (***finite element analysis results***)	**11.5**	**65%**

based on die footprint

- **Reduced thermal resistance by 58% to 65%** with the advanced evaporator design compared with state-of-the-art cooling system.
- Enhancements enable **increased device power densities.**

* Calculated using one side of the die (12.78 mm   12.78 mm)

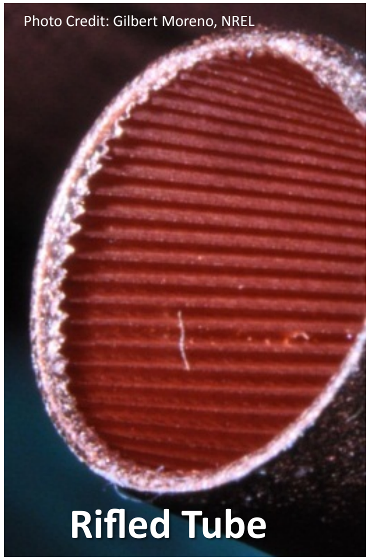
* Performance from: Sakai, Y., and Ishiyama, H., 2007, "Power Control Unit for High Power Hybrid System," SAE International

Technical Accomplishments and Progress

Characterized and Enhanced Condenser Thermal Performance

Refrigerant	R''_{th} (cm^2- K/W)		
	Plain Tubes	Rifled Tubes	Reduced R''_{th} with Rifled Tubes
HFC-245fa	**9.30**	**7.58**	**18%**
HFO-1234yf	**8.12**	**6.06**	**25%**

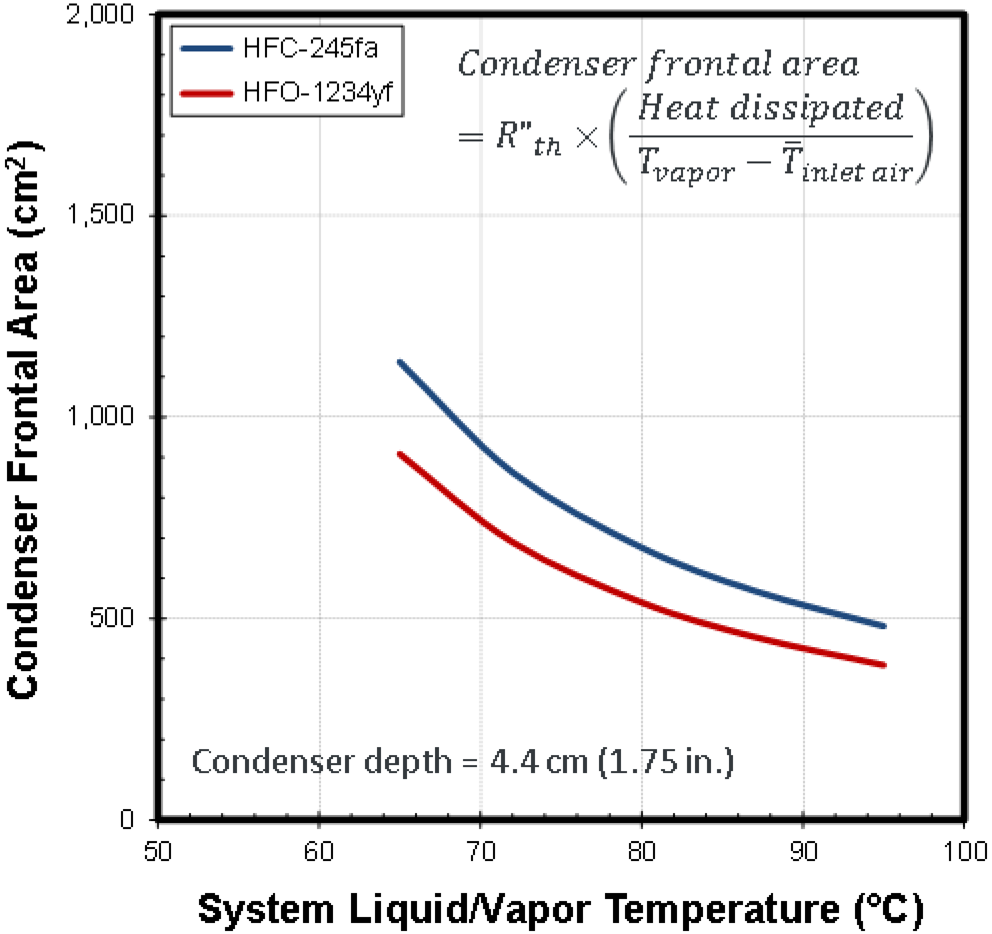
$$R''_{th} = \frac{(T_{vapor} - \bar{T}_{inlet\ air})}{Heat\ dissipated} \times Condenser\ frontal\ area$$



- Evaluated two condenser designs: plain tube condenser and rifled tube condenser.
- Increased condensation heat transfer coefficients using rifled tubes. Rifled tube enhancements decreased thermal resistance by 18% for HFC-245fa and by 25% for HFO-1234yf. Decreasing the condenser thermal resistance allows for a more compact condenser.
- HFO-1234yf provided higher condensation heat transfer coefficients compared with HFC-245fa. HFO-1234yf's higher heat transfer resulted in 13% to 20% lower condenser thermal resistance compared with HFC-245fa.

Technical Accomplishments and Progress

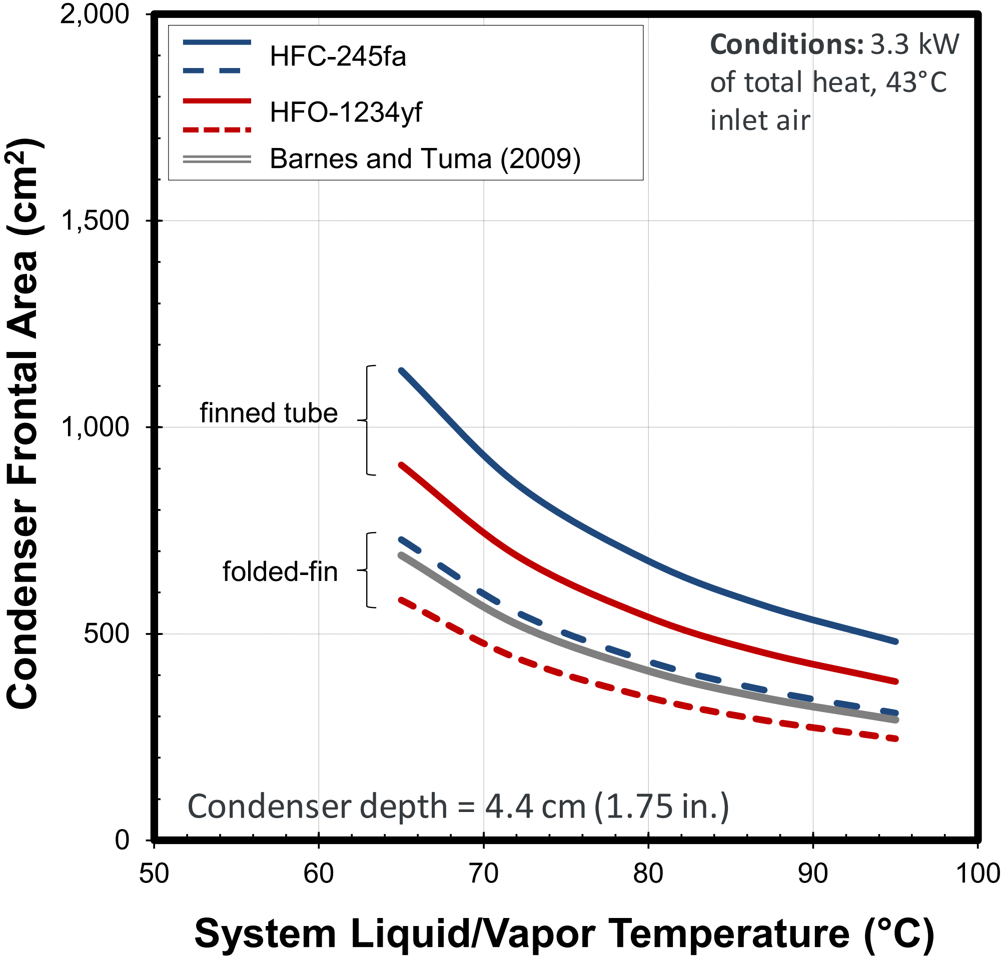
Air-Cooled Condenser Size Requirements (Finned-Tube Condenser)



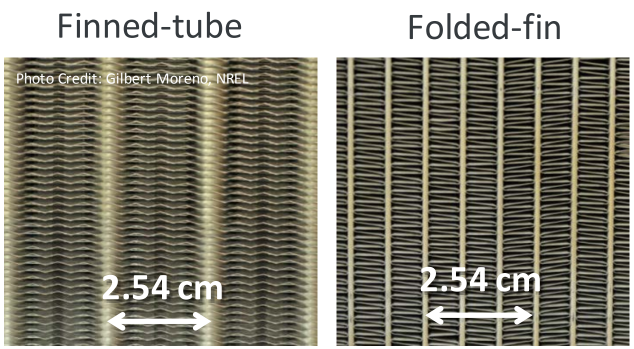
- Estimated condenser frontal area/size requirements at various refrigerant temperatures for the following operating condition:
  - 3.3 kW of total heat (estimated heat dissipation from a 95% efficient, 55-kW inverter), 43°C inlet air.
- Higher refrigerant temperatures enable a more compact condenser.
- HFO-1234yf's higher performance allows for a smaller condenser.

Technical Accomplishments and Progress

Conducted Analysis to Estimate Size Requirements for Folded-Fin Condenser



- Estimated the size requirements for a brazed folded-fin condenser → matched air-side surface area (assumed air-side was the dominant thermal resistance).

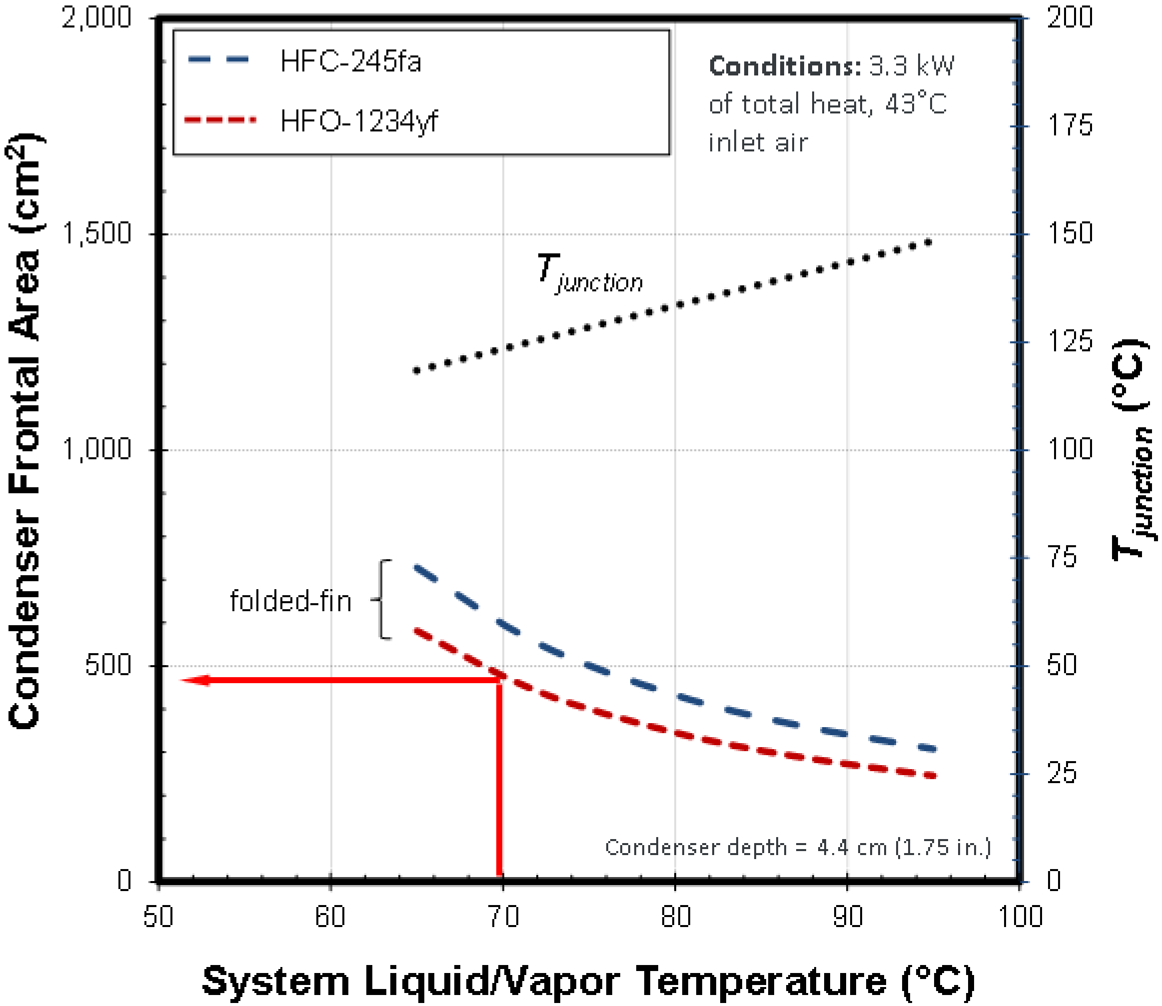


~36% more air-side surface area for folded-fin condenser

- Greater air-side surface area of the folded-fin design allows for a more compact condenser.
- Condenser results are consistent with those reported by Barnes and Tuma (2009).

Technical Accomplishments and Progress

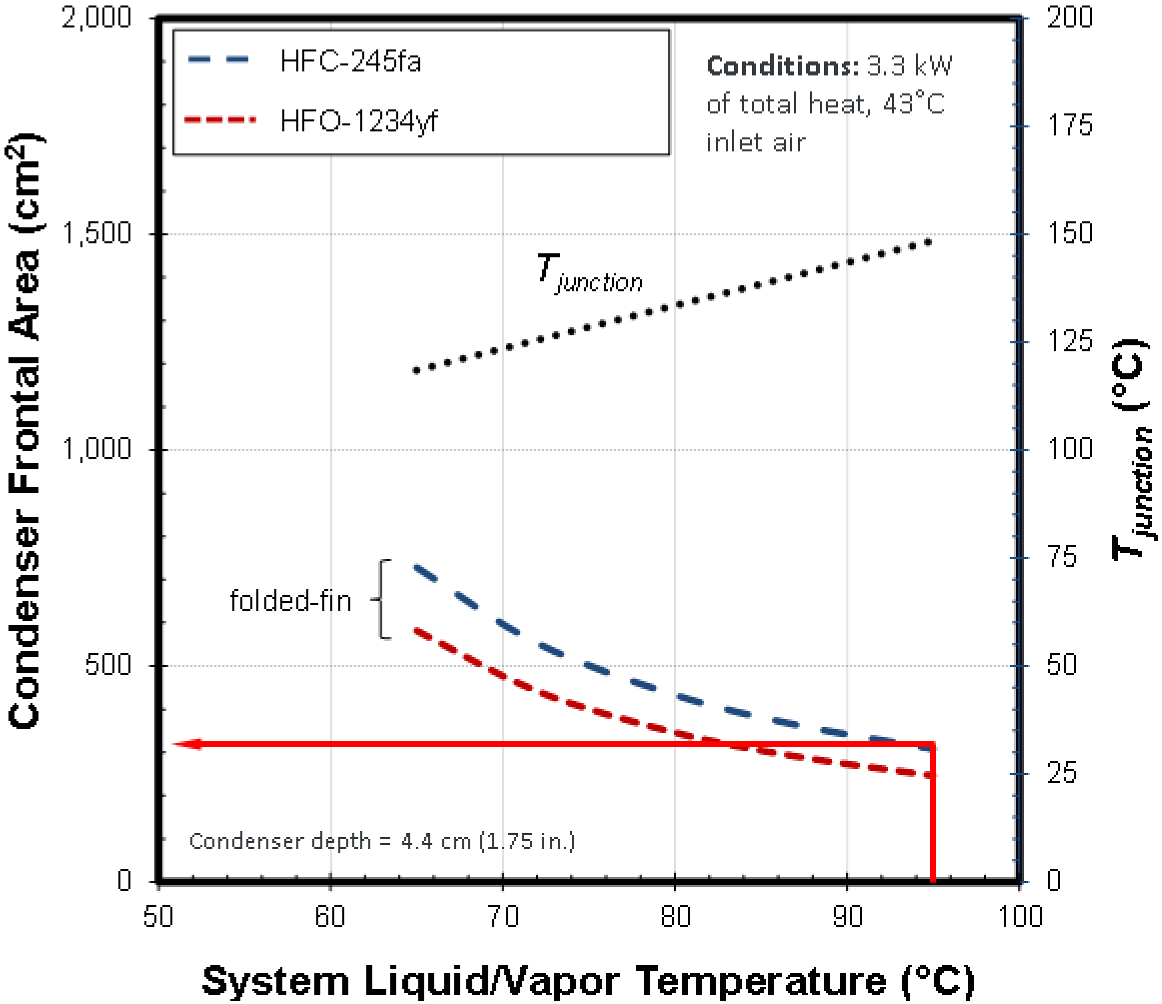
Air-Cooled Condenser Size Requirements (Folded-Fin Condenser)



- For lower system temperature applications typical of automotive power electronic coolant temperatures (70°C), HFO-1234yf is recommended because its greater performance allows for a smaller condenser.
- With HFO-1234yf at 70°C, the required condenser frontal area is ~470 cm^2.
- At 70°C, HFO-1234yf pressure is ~300 psia.
- Estimated junction temperature using advanced evaporator design and six Delphi power module configuration is 125°C.

Technical Accomplishments and Progress

Air-Cooled Condenser Size Requirements (Folded-Fin Condenser)



- If higher temperature operation is allowed or required (i.e., wide-band-gap devices), HFC-245fa may be a better choice because of its higher critical temperature and lower pressure.
- With HFC-245fa at 95°C, the required condenser frontal area is reduced to ~310 cm^2.
- At 95°C, HFC-245fa pressure is ~164 psia.
- Estimated junction temperature using advanced evaporator design and six Delphi power modules configuration is 150°C.

Responses to Previous Year Reviewers' Comments

Reviewer Comments/Questions:

"The reviewer pointed out that this concept has some special requirements, such as condenser location above the evaporator and in a location with adequate air flow for the fan. The reviewer cautioned that these physical requirements could cause interference with other components and increase the space required."

"The reviewer opined that the approach is novel and the results do indicate that it is technically capable of cooling the switches. The reviewer recommended that more involvement with the overall packaging of the inverter and the cooling system is needed to provide a solution."

"The reviewer said that resources have been sufficient to date as the results are impressive, but that vehicle level integration support is needed to move the project to the next level."

Response: We agree with the reviewer comments/suggestions and are addressing them in the following manner:

- Developing alternative variations to the condenser to reduce cooling system size and packaging constraints.
- Decreased the size and increased the performance of the evaporator.
- Meeting with industry OEMs and inverter suppliers to better understand packaging requirements and to develop collaborations to build a two-phase cooled inverter.

Collaboration and Coordination with Other Institutions

Industry Partners

- **Delphi** (supplied power modules)
- **3M Electronics Markets Materials Division** (supplied boiling enhancement coating)
- **DuPont** (supplied HFO-1234yf refrigerant)

University Partners

- **University of Colorado–Boulder** (graduate student)
- **Iowa State University** (provided enhanced surfaces)
- **University of Illinois–Chicago** (provided enhanced surfaces)

Remaining Challenges and Barriers

Challenges and Barriers:

- Two-phase is not used to cool automotive power electronics. There are reliability and cost concerns associated with the technology.
- Packaging of the cooling system presents a challenge.

Strategy:

- Propose a simple two-phase cooling solutions (indirect cooling, passive, low-cost materials, minimize refrigerant requirements).
- Propose solution with pressures equivalent or lower than those used in vehicle air-conditioning systems.
- We are working to develop industry partnerships to demonstrate a two-phase cooled inverter system.
- Two-phase cooling technology is used in the vehicle air-conditioning systems. Technology is available to develop reliable refrigerant-based cooling systems.

Proposed Future Work

FY14

- Bond a Delphi power module to the advanced evaporator using a thermoplastic bonded interface.
- Experimentally characterize the junction-to-liquid thermal resistance.
- Evaluate the effect of cooling system inclination/orientation on thermal performance.
- Experimentally quantify key system metrics (thermal resistance, coefficient of performance, volume, weight) and compare against conventional cooling systems.
- Develop industry partnerships to demonstrate a two-phase cooled inverter system.

Summary

DOE Mission Support

- Accelerate the adoption of electric-drive vehicles through improved thermal management.
- Support the President's EV Everywhere Challenge.

Approach

- Utilize the high heat transfer rates of two-phase cooling to improve performance.
- Demonstrate a passive, two-phase cooling solution for automotive power electronics.

Accomplishments

- Demonstrated that an inverter-scale passive two-phase cooling system can dissipate at least 3.5 kW of heat (steady-state) with only 250 mL HFC-245fa.
- Improved evaporator design (advanced evaporator concept) to increase performance, reduce size, and reduce refrigerant requirements.
- Reduced junction-to-fluid resistance by 58% to 65% with an advanced evaporator design. Enhancements are relative to state-of-the-art cooling system.
- Conducted an analysis to estimate required condenser size at various refrigerant temperatures.

Summary

Future work

- Bond a Delphi power module to the advanced evaporator using a thermoplastic bonded interface.
- Experimentally characterize the junction-to-liquid thermal resistance.
- Evaluate the effect of cooling system inclination/orientation on thermal performance.
- Experimentally quantify key system metrics (thermal resistance, coefficient of performance, volume, weight) and compare against conventional cooling systems.
- Develop industry partnerships to demonstrate a two-phase cooled inverter system.

Collaborations

- Delphi
- 3M
- DuPont
- University of Colorado–Boulder
- Iowa State University
- University of Illinois–Chicago

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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